

## Novel Design Elements of the Space Technology 5 Mechanical Subsystem

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**Abstract.** This paper describes several novel design elements of the Space Technology 5 (ST5) spacecraft mechanical subsystem. The spacecraft structure itself takes a significant step in integrating electronics into the primary structure. The deployment system restrains the spacecraft during launch and imparts a predetermined spin rate upon release from its secondary payload accommodations. The deployable instrument boom incorporates some traditional as well as new techniques for lightweight and stiffness. Analysis and test techniques used to validate these technologies are described. Numerous design choices were necessitated due to the compact spacecraft size and strict mechanical subsystem requirements.

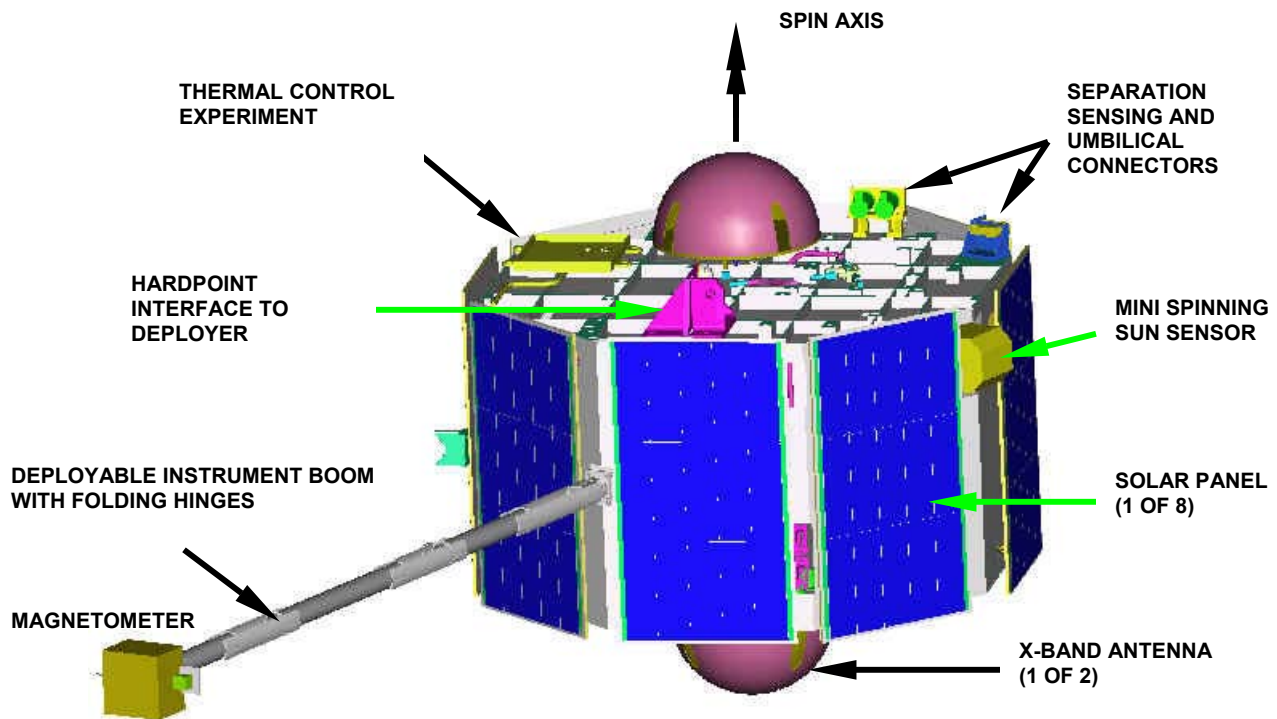
### Introduction

The Space Technology 5 (ST5) Mission is a constellation of 3 fully functional micro-spacecraft. It is designed to pave the way for future missions requiring 50 to 100 Nanosatellites that perform large-scale, in-situ magnetospheric mapping. Each 25 kg, spin-stabilized spacecraft carries a miniature science-grade magnetometer and multiple innovations and technologies for spacecraft scale-reduction.

The spacecraft shown in Figure 1 is an octagon, 60 cm across and 30 cm in height. The ecliptic pole-pointing spin axis is normal to the decks, allowing sun exposure to the eight solar arrays covering each side. The magnetometer instrument is deployed on a folding boom 80 cm from the nearest solar panel.

This paper describes how the ST5 structural subsystem enables scale reduction in three main design elements.

- An electronics enclosure, which houses vital power and computing boards, is itself the backbone or “heart” of the structure.
- An innovative Deployer Structure supports the spacecraft at three distinct points through launch, and then imparts the required spin rate for mission operations.
- A collapsible boom with carpenter tape hinges deploys the magnetometer to a fixed location suitable for precise measurements.



*Figure 1. ST5 Satellite in On-orbit Configuration*

### **Design Philosophy**

Principles constituting the design philosophy are vital for the scale-reductions required to make future nano-satellites possible. These principles form an undercurrent for most major design decisions on ST5.

#### ***Cast Card Cage Multifunctional Structure***

The central power and computer electronics box is incorporated into the main structure.

#### ***Kinematic Hardpoint Interface to Deployer***

Securing the spacecraft at the corners -instead of with a circular “V” Band- maximizes available deck area for experiments and systems.

### ***Small Scale Mechanisms and Actuators***

Mechanisms and actuators are of a compatible scale with the instruments/payloads they deploy.

### ***“Ship & Shoot”***

The mission design envelopes worst-case environments as defined in an advanced launch vehicle study and available secondary payload provider user guides. Thus ST5 can launch on almost any secondary payload adapter.

### ***Bench-Top Assembly***

A Top Deck swings away for interior access. The sides are closed in with two sheet metal “clam-shells” for minimum weight. The Solar Panels are easily detachable.

### ***Structural Performance***

Honeycomb sandwich structures form the Deployer base and solar panel substrates. These efficient designs were implemented wherever possible for increased stiffness and weight savings.

## **Design Elements**

### ***Multi-Functional Structure***

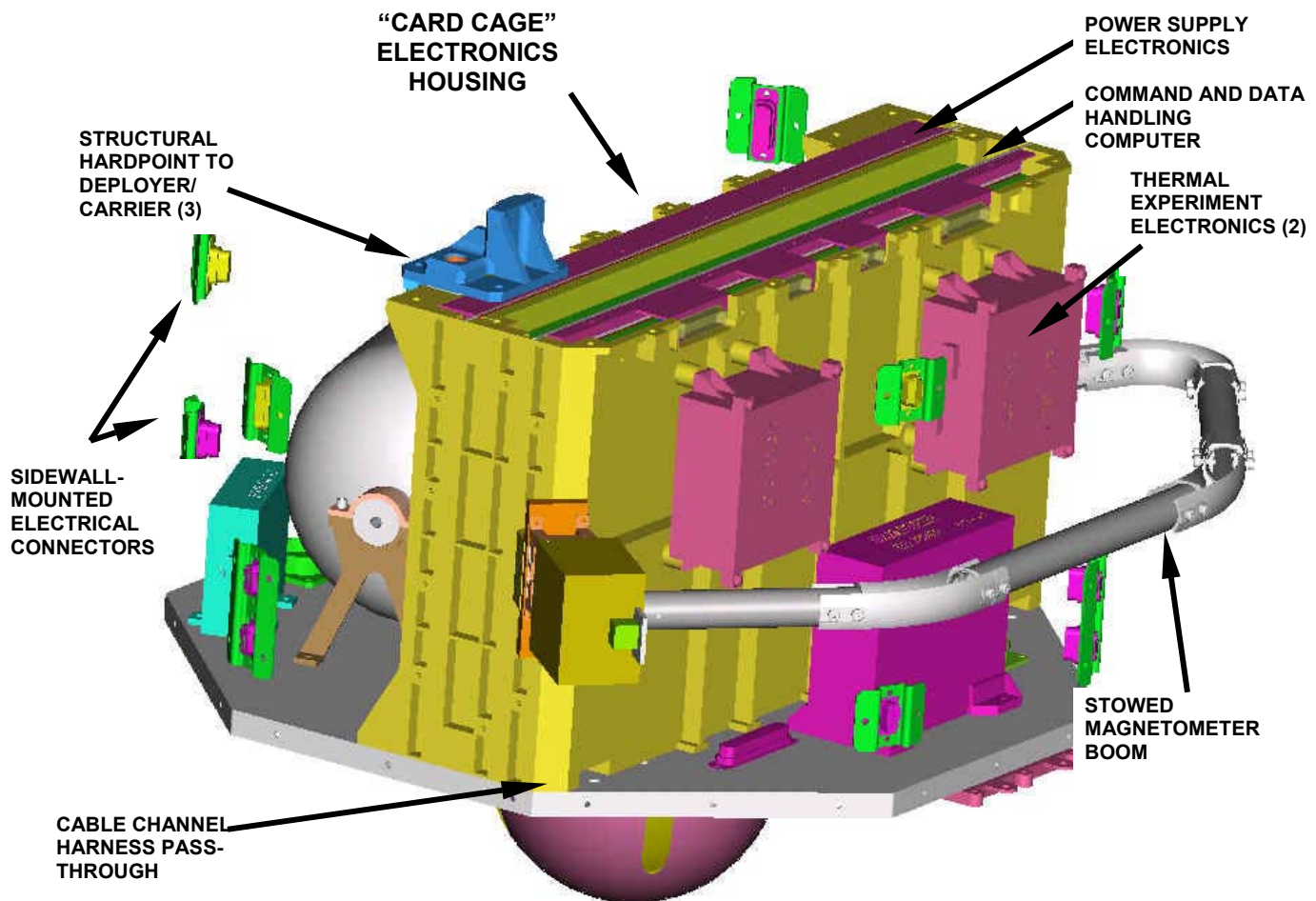
The heart of the spacecraft, both electronically and structurally, is the investment-cast “Card Cage” shown in Figure 2. This assembly is the nerve-center, accommodating wiring harness for command and power signals for the entire spacecraft. The Card Cage is the primary structural load path, since it spans the spacecraft width and ties the decks and all three hardpoint interfaces to the Deployer Structure. The monocoque design means negligible forces are transferred to the electronics inside. Three additional electronics boxes and the boom are mounted to the Card Cage exterior, making it the veritable core of the spacecraft.

The Card Cage would not have been possible without the recent advances in investment casting technology. The walls are as thin as .065” (1.5mm) over relatively long spans. Despite this, machining tolerances are held to less than .005” (.1mm). Casting tolerances

are less than 0.02” (0.5mm) over the maximum 18” (45cm) dimension. Deep pockets, undercuts, and complex contours are easily accommodated at low cost. There exists now significant heritage to electronics box casting, and finished product strengths of 27 ksi (190 MPa) meet the primary load path requirements.

Removing the top deck allows access to the electronics inside. Each card is restrained by off-the-shelf wedge-type locks in as-cast guide rails. A mother board at the bottom allows communication between the electronics and the outside of the card cage.

The passive thermal design enhances both conductive and radiative heat transfer. Each board consumes ~10W at peak power. All conductive interfaces have an Iridite finish, while the radiative surfaces are black-anodized. Most components in the spacecraft are also black anodized for the same reason. Heat conducts through the Card Cage walls to the decks, where it is then radiated to deep space. Heat loss is controlled by multi-layer insulation on each deck.



**Figure 2. Structurally-Integrated Electronics Housing  
-Top Deck and Sidewalls Removed**

### ***Deployer Structure***

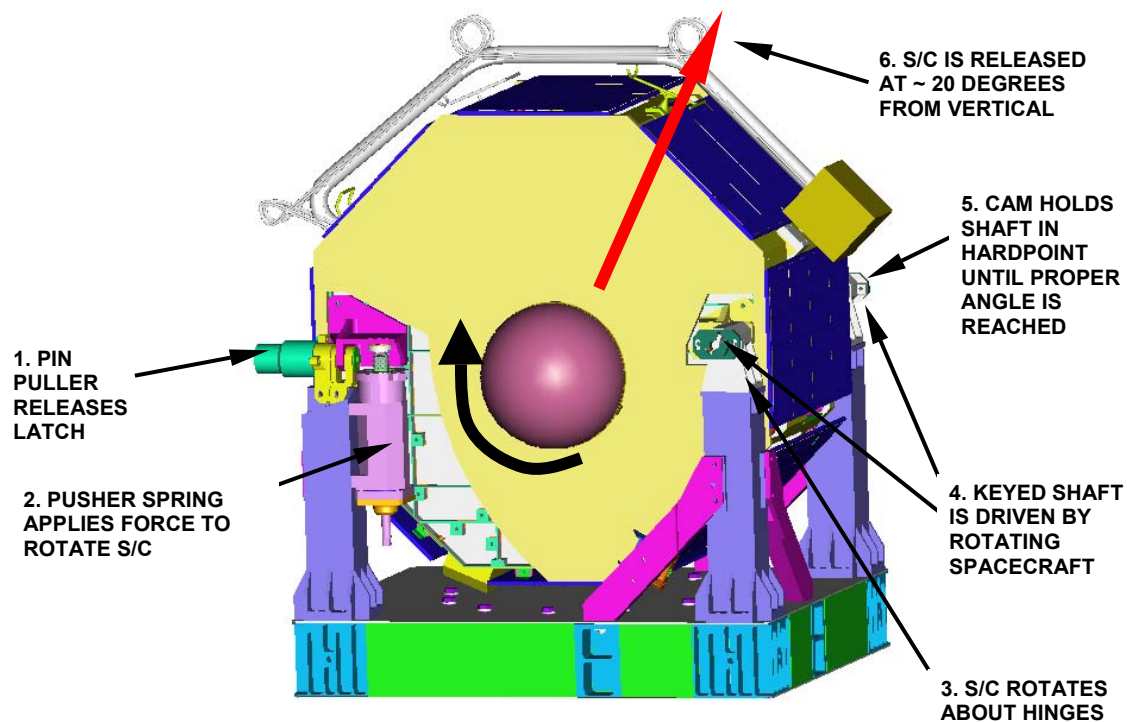
The Deployer Structure (DS) with a three-point kinematic hardpoint release mechanism secures the spacecraft to the launch vehicle. The entire DS and spacecraft fit inside a 24" (60 cm) cube envelope, and are designed to withstand structural loads of 20 G static and 17.1 Grms dynamic.

The DS is composed of a 3" (8cm) thick aluminum honeycomb sandwich base, 2" (5cm) tubular stanchions at three corners, and mechanisms at the stanchion tops to hold the spacecraft. This design replaces the traditional shear ring and "V" Band in order to maximize available area on both decks, and impart the initial spacecraft stabilizing spin. The spin-up and release sequence is described in Figure 3.

A Shape-Memory Alloy (SMA) Pinpuller from TiNi Aerospace initiates the deployment sequence. This low-shock actuator is needed because of sensitive components packaged in close proximity.

The spin rate for the entire mission is determined upon initial separation from the launch vehicle due to the lack of a spin vector thruster. The DS is tested in a thermal vacuum chamber by deploying the engineering unit spacecraft with both the spin axis and the push-off direction horizontal to minimize any gravity effects. A “front flip” is achieved with the pusher shown in Figure 3 at the top, and a “back flip” with the pusher at

the bottom. The spin rate is measured by high-speed video at 1ms exposure frames every 4ms. Four total configurations have been tested; front flip and back flip rotation at each temperature extreme of  $-30^{\circ}\text{C}$  and  $+60^{\circ}\text{C}$ . The majority of the spin rate error is due to compliance in the test fixture. The 6' (2m) high welded “A-frame” moved  $\sim .06"$  (1.5mm) under the 100 lbf (440N) initial push-off force. Accounting for known errors, spin rate predictions are well within the tolerance goal of 10%. Compliance of the launch vehicle will be assessed when calculating and setting the pusher force for launch.



**Figure 3. ST5 Release Sequence from Deployer Structure**

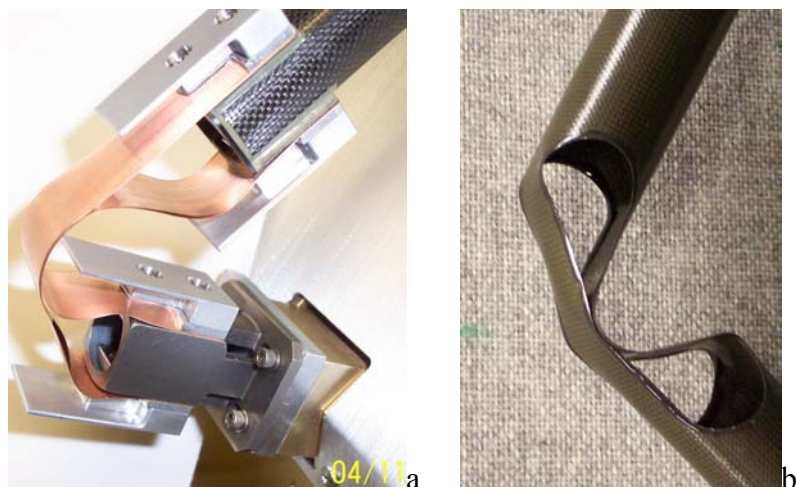
### ***Instrument Boom with Integral Folding Hinges***

Many mechanisms are large compared to their supported “payloads,” impacting overall mass. The boom wrap-around design requires three hinges. Implementing the required motion with traditional multi-part hinges would have swamped the mass budget and incurred much specialized engineering in designing for friction, damping, and ensuring positive torque-ratios. The current design with integral folding hinges and no sliding parts has avoided those issues.

The boom positions the magnetometer instrument 80cm from the spacecraft to within  $\frac{1}{4}^\circ$  and 1 cm repeatability. Its natural frequency is tuned to between 5 and 11 Hertz, to meet science data requirements. The boom is comprised of three  $\varnothing \frac{3}{4}$ " T300 graphite composite rods with Titanium adapters at each end for “carpenter tape” hinge links. These folding hinges are  $\frac{1}{2}$ -hard Beryllium-Copper tapes, .006" (.15mm) thick. A detail is shown in Figure 4a. This design weighs ~0.35 lb (170grams), about twice the instrument mass, and is magnetically clean, allowing measurements as low as 10 Nano Tesla when deployed.

When stowed, the boom folds around three sides of the spacecraft, supported off the solar panels by intervening snubbers. A low-shock Pinpuller from TiNi Aerospace releases the instrument from its latch.

A monolithic, graphite fiber composite boom, hinge detail shown in Figure 4b, has also been built and tested as a part of early ST5 development. It weighs 0.1 lb (45grams), half of the supported instrument. While graphite fiber is not normally considered a flexible material, this design allows the boom to bend over  $90^\circ$  and has many features that make it optimum for its intended use. The graphite provides an electrically conductive path to bleed off static charge—a great benefit on the highly charged mission orbit. It resists creep and remains stable under large temperature fluctuations, allowing for precise science measurements even under direct solar radiation. The thermal conductance is optimum for controlling heat loss from the spacecraft. Unfortunately, to meet stiffness and stowing requirements, it would have had a 50% larger diameter, casting a larger shadow on the solar arrays. Therefore ST5 uses the smaller design with metallic folding hinges. The MAG Con mission is using this monolithic boom as a baseline.



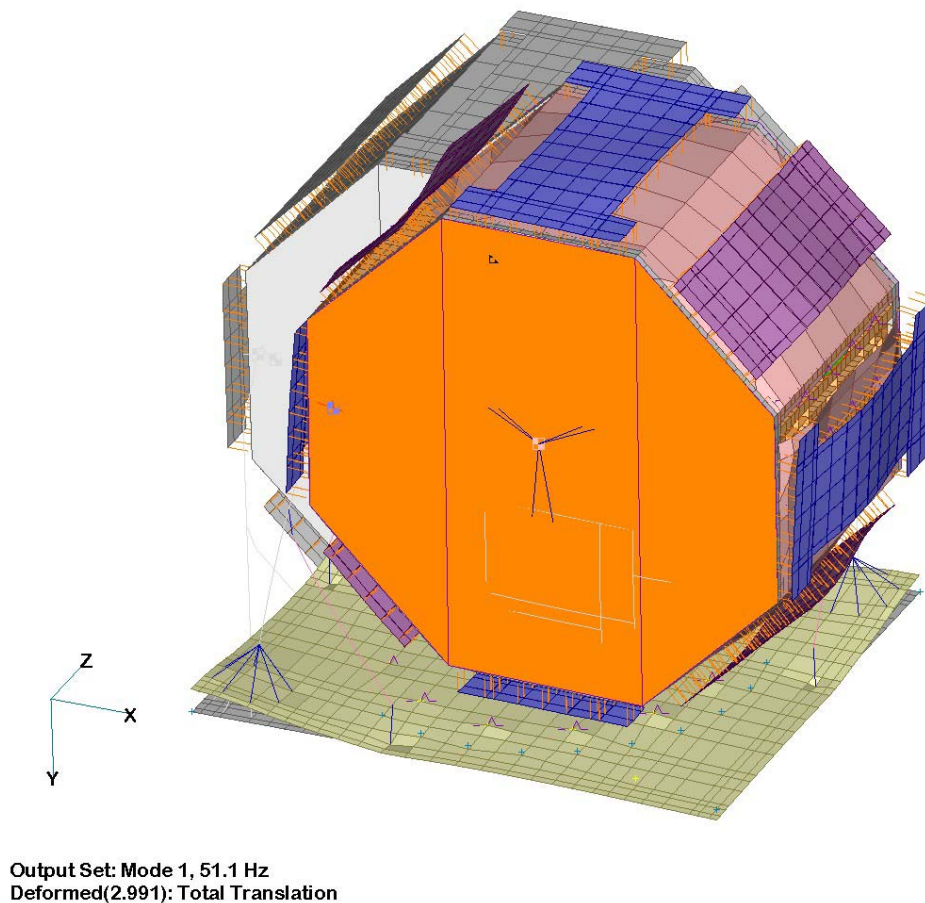
***Figures 4a. and 4b. Magnetometer Boom Hinge Detail  
-BeCu and Graphite Composite***



## **Engineering Tools for Design, Analysis and Test**

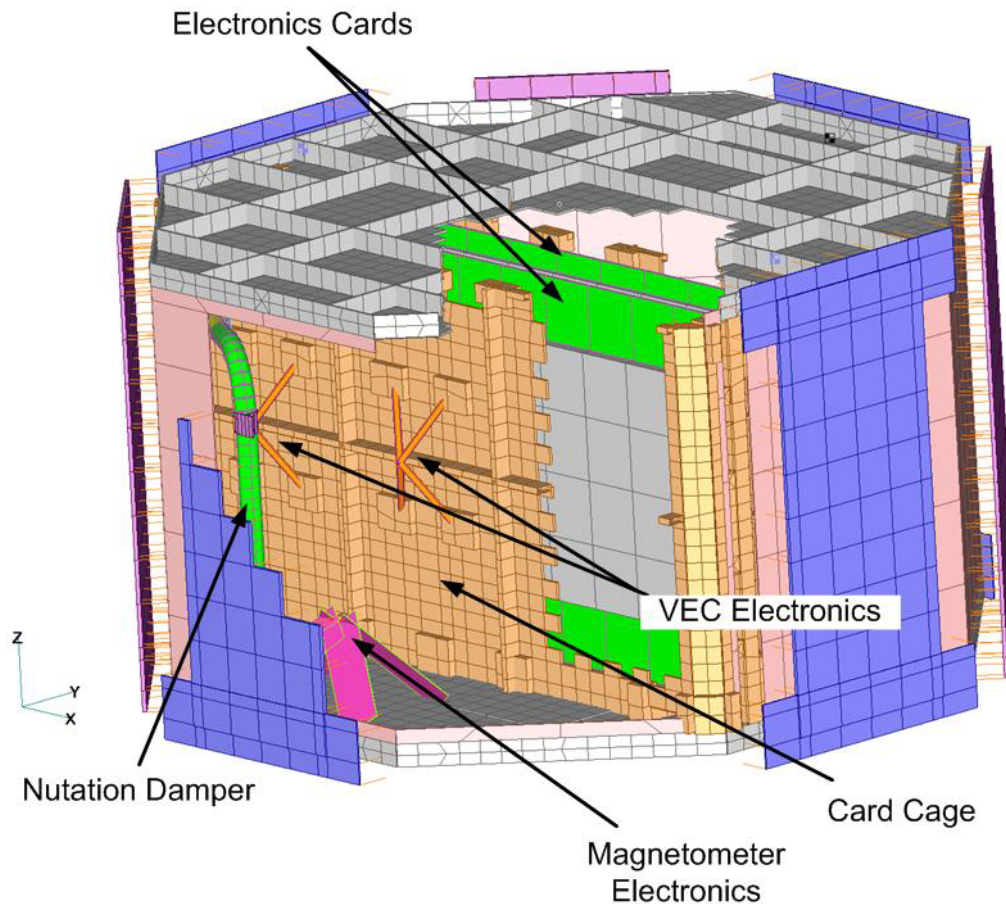
The ST5 Structure and all-up assembly design was accomplished with ProEngineer 2001<sup>®</sup> CAD software. FEMAP<sup>®</sup> version 8.1 as a NASTRAN pre- and post-processor, and classical analytical techniques with MathCAD or Microsoft EXCEL calculating tools yielded stress analysis results. Mechanism and deployment analysis was performed with Working Model 3D<sup>®</sup> and ADAMS<sup>®</sup> kinematic and dynamic modeling software. These packages mesh elements directly from CAD solid geometry. This powerful suite allows the analyst to conduct “what-if” scenarios quickly from CAD models accessed through a shared database.

The ST5 finite element model (FEM) shown in Figures 5 and 6 was developed for use with static, normal modes, buckling, and dynamic solution sequences. The FEM consists of approximately 10,000 elements and grid points which include a combination of scalar (spring), one-dimensional (beam) and two-dimensional (plate) elements. The analysis is streamlined using Visual Basic for Applications to link FEM output to spreadsheets with pre-programmed “hand” analysis routines. Output data from an element/node of interest is automatically transferred from the FEM user interface to perform typical analysis tasks on the spreadsheet.



***Figure 5. ST5 Spacecraft FEM Predicted First Lateral Model***

### Cut-Away View

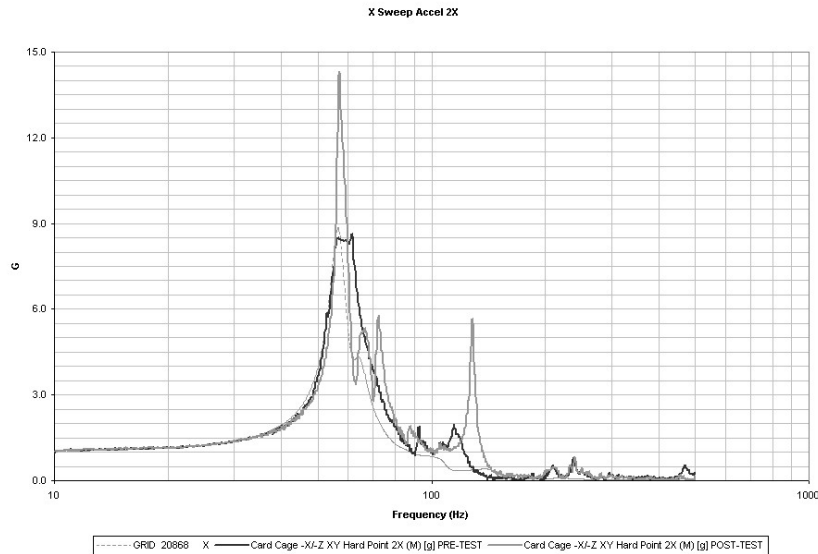


**Figure 6. ST5 FEM Analysis Tools Allow Visual Interpretation of Results**

To correlate test data, vibration results are written to universal files for transfer to a GSFC-developed Microsoft EXCEL package. Data overlays, modal correlations, and peak-enveloping are readily performed in this way, without the inconvenience of reams of printed

results. The frequency response data obtained from a recent vibration test of the ST5 engineering test unit overlaid with finite element predictions is shown in Figure 7. Primary modes less than 100 Hz from the vibration test match the FEM within 5%.





**Figure 7. ST5 Spacecraft Comparison of Test and FEM Analysis Results**

### Conclusion

Upcoming science programs such as the Magnetic Constellation mission already use the ST5 system as a baseline. Many future missions will benefit from the multi-functional structures, lightweight deployables and innovative design developed on the ST5 system.

The ST5 structural system completes qualification testing and final checkouts of the structure and mechanisms in the summer of 2003. Integration and assembly of the flight components starts in the fall of 2003.

### Acknowledgements

The authors wish to acknowledge the following persons for their invaluable contributions to the ST5 development. Mr. Suk Yoon of Swales Aerospace, Inc. is chief designer for the ST5 mechanical system. With a fantastic work ethic and decades of experience designing spacecraft, Mr. Yoon was critical to the development of ST5. Mr. Rick Scott of NASA – GSFC conceived and built the Deployer mechanisms, applying his mechanisms expertise to the realization of a robust and practical system. Ms. Christine Collins of NASA – GSFC and John Bowkett of NuCast, Inc, were instrumental in bringing the Card Cage through final design and fabrication.